A dynamical life cycle inventory of steel, aluminium, and composite car bodies-in-white

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Outline

• Aim
• Method
• Case study
• System Dynamics model
• Results
• Conclusions
• Recommendations
Aim

Life cycle assessment (LCA) method that can account for changes over time in:

Resource consumptions
- Energy
- Water
- Materials

Environmental impacts
- Resource depletion
- Global warming potential
- Photo oxidant creation potential
- Acidification potential
- Ozone depletion potential
- Water pollution
- Solid waste
- Etc.

Life cycle inventory

Life cycle assessment
Method

System Dynamics model
STELLA™
Dynamical computations
Output: car fleet distribution
Method – System Dynamics

• *Dynamics*: the way that the state of a system changes over time in response to:
  – internally-generated (endogenous) forces
  – externally-imposed (exogenous) forces
Method – System Dynamics

Stocks and flows

• Filling and draining a stock

• Operate at finite rates
• Source of delay
• Source of inertia

(Meadows 2009, p97)
Feedback loops

- A change in a stock feeds back around a loop to adjust the original change

- Reinforcing: *amplifies* change
- Balancing: *resists* change

(Meadows 2009, p42)
Method – System Dynamics

The basic car life cycle
Method

System Dynamics model
STELLA™
Dynamical computations
Output: car fleet distribution

Life cycle inventory
MS Excel
Linear calculations
Output: life-cycle energy consumption
Case study

**Body-in-white**

Load-carrying welded frame to which other moving components are attached
Case study

2 scenarios

Steel

sub with

sub with

Aluminum

Carbon-fibre reinforced polypropylene

• Australian context
System Dynamics model
System Dynamics model

Main assumptions

• Production
  – *Demand for cars* grows with *population*
  – *Demand for cars* is met first by *recycled LW*, then *virgin LW*, then *steel*

• Adoption
  – Lightweight BIWs are adopted (*S-shaped*) in 2010-2030
  – *Market share* of each type of car is a function of *total cost of ownership*

• Use
  – *Driving intensity* is the same for all cars (15,500 km/year)

• Retirement
  – *Useful life* is the same for all cars (22 years)
  – *BIW retirement rate* is 1/22\(^{nd}\) of *car fleet* per year

• Recycling
  – *Recycled lightweight materials* are used only for *new BIWs*
System Dynamics model

The basic car life cycle

Initially…
6 million

22 years
System Dynamics model

The life cycle of each type of car

Initially...
6 million
System Dynamics model

Production priority:

1. Recycled lightweight
   (if raw material is available)

2. Virgin lightweight
   (if manufacturing capacity is available)

3. Steel
   (meet the remaining demand)

Initially…
6 million
System Dynamics model

Lightweight cars are retired...

Initially... Zero
System Dynamics model

Lightweight cars are retired... ... and recycled

Initially... Zero
System Dynamics model

Initially...

1.0

Fraction of Steel Car Manufacturers

[$\times$] Market Sharing

Fraction of Lightweight Car Manufacturers

Manufacturers share the market...
Based on the total cost of ownership, manufacturers share the market... 
... based on the total cost of ownership.
System Dynamics model

Transition is S-shaped growth of lightweight cars

20 years
System Dynamics model – results

Car fleet

![Graph showing the evolution of car fleet over years with different scenarios.](image)

- **Reference**
- **Historical**
- **CFR-PP scenario**
- Aluminium graph is similar
System Dynamics model – results

Car fleet

R loop *amplifies* growth of recycled BIWs

B loop *resists* growth of virgin BIWs

- Substitution of steel with composite
53% of production is LW, but only 22% of the fleet is LW

Slow turnover!
System Dynamics model – results

- Source of *delay* (slow turnover!)
- Production > Retirement → *Growth*
Life cycle inventory
# Key data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steel</th>
<th>Aluminium</th>
<th>Composite</th>
<th>Units</th>
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<tbody>
<tr>
<td>BIW mass</td>
<td>430</td>
<td>300</td>
<td>230</td>
<td>kg</td>
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<tr>
<td>Car mass</td>
<td>1720</td>
<td>1590</td>
<td>1520</td>
<td>kg</td>
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<td>Car fuel consumption</td>
<td>9.0</td>
<td>8.67</td>
<td>8.48</td>
<td>l/100km</td>
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<tr>
<td>Total cost of ownership</td>
<td></td>
<td></td>
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<tr>
<td>Initial (2010)</td>
<td>58,000</td>
<td>54,900</td>
<td>54,300</td>
<td>$</td>
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<tr>
<td>Final</td>
<td>96,900</td>
<td>92,500</td>
<td>90,300</td>
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<td>Energy flow, production</td>
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<td>Virgin</td>
<td>35.2</td>
<td>190</td>
<td>102</td>
<td>MJ/kg</td>
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<tr>
<td>Recycled</td>
<td>19.0</td>
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<td>MJ/kg</td>
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<td>Energy flow, use</td>
<td>2.47</td>
<td>2.57</td>
<td>2.64</td>
<td>kJ/km/kg</td>
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</tbody>
</table>
Life cycle inventory – results

Energy consumption

- Steel
- Steel & Aluminium
- Steel & Composite

substitution of steel with lightweight material

Both scenarios
Life cycle inventory – results

Energy consumption

90% of energy is from petroleum consumption during use

substitution of steel with lightweight material
Life cycle inventory – results

Energy consumption

Energy investment is recovered
Composite is better than aluminium
Energy is always growing!

substitution of steel with lightweight material

Energy consumption (pJ/y)
Year

1980 2000 2020 2040 2060 2080

Steel
Steel & Aluminium
Steel & Composite
Conclusions

- A System Dynamics approach provides greater *insight* than standard life cycle inventory.
- A SD approach reveals:
  - a long *delay* in the transition to lightweight cars.
  - material-substitution’s small effect on the *fleet*’s energy, rather than its large effect on a *single product*’s energy.
- Case study simulations show:
  - the *energy benefits* of composite cars emerge *much sooner* and are about *twice as large* in the long-term as those of aluminium cars.
  - energy consumption always *grows*. 
Recommendations

- Material-substitution, alone, has low leverage for reducing energy consumption
  - Too much investment for too little benefit

- Might get better results from adjusting:
  - synergistic tech innovations (e.g., LW + electrification)
  - fuel supply
  - driving intensity
  - driving behaviour

Future work
Questions?
Characteristics of cars

Powertrains are adjusted for equal power-to-weight ratio

LW cars are fuel efficient
Life cycle inventory – key data

Energy consumption of materials

High energy investment... is recovered during use

(Puri et al. 2009)
SD model – key data

Fuel price drives materials prices

And all prices drive TCO

Total cost of ownership